

New Black Widows and Redbacks in the Galactic Field

Mallory S.E. Roberts

*Eureka Scientific, Inc. Oakland, CA USA
with the Fermi Pulsar Search and GBT Drift Scan Survey Collaborations*

Abstract. There has recently been a large increase in the number of known eclipsing radio millisecond pulsars in the Galactic field, many of which are associated with *Fermi* γ -ray sources. All are in tight binaries ($P_b < 24$ hr) many of which are classical “black widows” with very low mass companions ($M_c < 0.1M_\odot$) but some are “redbacks” with probably non-degenerate low mass companions ($M_c \sim 0.2M_\odot$). I review the new discoveries, briefly discuss the distance uncertainties and the implications for high-energy emission.

Keywords: millisecond pulsar; black widow; redback; accretion; eclipsing; binary; GBT; Fermi
PACS: 97.60.Gb; 97.80.Hn; 95.85.Bh; 95.85.Pw

BLACK WIDOWS AND REDBACKS

There is a subclass of MSPs in tight orbits ($P_b < 24$ hr) which have very low mass companions ($M_c < 0.05M_\odot$) and tend to exhibit eclipses. The first of these discovered was PSR B1957+20, a 1.6 ms pulsar in a 9.2 hr orbit around a $\sim 0.02M_\odot$ companion [13]. The radio pulsar regularly eclipses over $\sim 10\%$ of the orbit, with the pulses becoming highly scattered at eclipse ingress and egress, which is direct evidence for significant amounts of intrabinary material [14]. The optical lightcurve of the companion shows large orbital variation, with a peak visual magnitude of ~ 20.3 . This demonstrates that the pulsar is heating the companion. $H\alpha$ imaging revealed a nebular bow shock, which is direct evidence for a strong pulsar wind [18]. *Chandra* X-ray imaging shows a point source and a nebular tail pointing in the opposite direction of the pulsar motion [21]. The X-rays from the point source are orbitally modulated and have a power-law spectrum [16]. The interpretation of these data is that either particle or γ radiation from the pulsar is ablating the companion, and will perhaps eventually evaporate it leaving an isolated pulsar. The compactness of the orbit and the relatively high spin down energy of the pulsar ($\dot{E} \sim 10^{35}$ erg/s) gives rise to this phenomenon. Because the pulsar seems to be destroying its companion, it is called the Black Widow pulsar.

Between 1988 and 2007, only two other eclipsing MSPs with very low mass companions were discovered in the Galactic field; J2051–0827 [20] and J0610–2100 [6]. Both have significantly lower \dot{E}/d^2 than B1957+20, assuming their respective NE2001 distances [8]. Many more “black widows” have been found in globular clusters. In addition, a related class of eclipsing MSPs with short orbital periods have been found, the first by Parkes in NGC 6397 [10]. These have companion masses of a few tenths of a solar mass. In cases where an optical counterpart has been identified, they often appear to have non-degenerate companions, suggesting they are still

in the late stages of recycling. I will therefore refer to these systems as “redbacks”, the Australian cousin to the North American black widow spider. A total of 18 black widows and 12 redbacks are listed on P. Freire’s website of globular cluster pulsars (<http://www.naic.edu/~pfreire/GCpsr.html>). However, globular clusters are distant objects, and measurements of \dot{P} are strongly affected by acceleration in the cluster gravitational potential. Therefore, nearby eclipsing MSPs in the Galactic field are highly desirable for studies of relativistic shock emission in these systems.

HIGH ENERGY EMISSION FROM AN INTRABINARY SHOCK

The pulsar wind can interact with ablated material producing an intrabinary shock front whose orientation changes in respect to Earth as a function of orbital phase. It is this shock front which obscures the pulsed emission during the eclipses. Arons and Tavani [3] developed a model of high energy shock emission for the original Black Widow. They predict that electrons could be accelerated to energies as high as 3 TeV in this system. Although the orbit is circular, the high energy emission could be orbitally modulated due to obscuration by the shock, intrinsic beaming of the particle acceleration and emission by the magnetic field orientation in the shock, and from Doppler boosting. The shock distance of only a few light seconds from the pulsar implies that the B field and magnetization parameter σ may be relatively high compared to the termination shock of an ordinary pulsar wind nebula. While the shock luminosity can depend on the shock distance, fraction of wind involved, pulsar magnetic field, optical emission of the companion, magnetization of the wind, and the ion fraction of the wind, the most important factor in determining the total emission is still simply \dot{E} .

An important question in estimating expected high-energy fluxes is how reliable are NE2001 distance estimates? Accurate parallax measurements (i.e ones with high significance measurements that are minimally affected by the Lutz-Kelker bias [22]) since 2001 show that the 20% error estimate is generally pretty good in the Galactic plane, but at mid to high Galactic latitudes where MSPs tend to be found, the NE2001 model systematically underestimates the distance (Fig. 1), often by as much as a factor of 2 [7]. This has been attributed to a poor estimate of the Galactic scale height for the gas in the model. This would imply estimates of \dot{E}/d^2 for new eclipsing systems in the field are likely overestimated by a factor of $\sim 2 - 4$. However, we now know that MSP masses can be as high as $2M_{\odot}$, and the radii are likely larger than 10 km [11] and so the moment of inertia may be about a factor of 2 larger than the canonical value used in calculating \dot{E} , countering the systematic effect of the distance underestimate.

NEW DISCOVERIES IN THE GALACTIC FIELD

New radio surveys designed to be sensitive to very fast pulsars in tight binaries have recently greatly increased the number of known MSPs in the Galactic field, including the number of black widows and redbacks. Large scale sky surveys with GBT and Parkes have so far discovered 2 new black widows and 2 new redbacks. The best studied of these is J1023+0038, discovered in the GBT drift scan survey [1, 2]. This 1.69 ms eclipsing

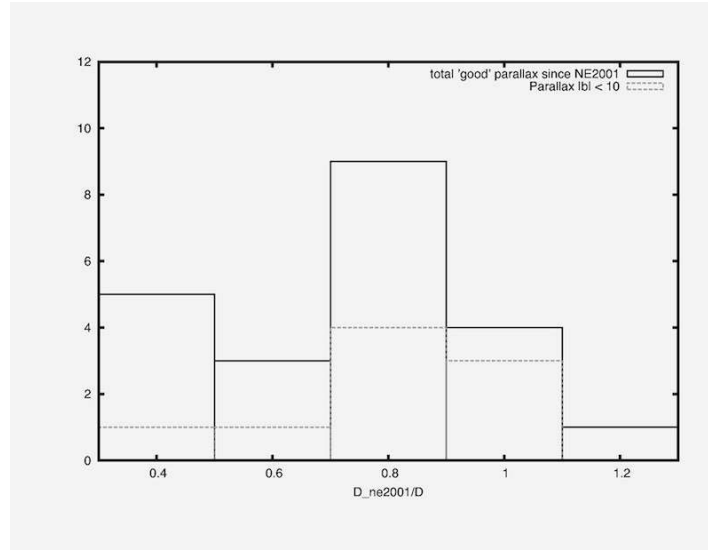


FIGURE 1. Histogram of the ratios of NE2001 distances to high confidence parallax measurements of pulsars since 2001 [22]. The solid black histogram is all measurements, the dashed grey is for pulsars at Galactic latitude $|b| < 10^\circ$

pulsar in a 4.8 hr orbit around a $\sim 0.2M_\odot$ companion is especially interesting because optical observations of the companion star in 2001 showed spectral evidence for an accretion disk. This further justifies the name “redback” for these systems, since this spider is one of only two known species where the male actively aids the female in eating him while mating.

The most productive means of finding field MSPs is proving to be searches of *Fermi* γ -ray sources. As of this time roughly 30 new MSPs have been discovered by searches with the Parkes, Nancay, Effelsberg, and especially the Green Bank Telescopes over the last 2 years [19, 4, 15, 5], including at least 4 black widows and 2 redbacks (the number is changing on an almost daily basis). Most show clear eclipses, including PSR J1810+17 with a spin period of 1.66 ms, second only to B1957+20 in spin period, but with a much shorter orbit of 3.6 hr, and PSR J2215+51 with a spin period of 2.61 ms and a minimum companion mass of $\sim 0.22M_\odot$. The two eclipsing systems from the drift scan survey are also *Fermi* sources, as is the original black widow. It should be noted that there is no strong evidence of unpulsed GeV emission in the *Fermi* data from these sources yet, with clear γ -ray pulsations observed from at least three of the black widows.

The table lists all the new systems that were announced by the time of the meeting. Many of these are actually quite bright in radio, and so may be amenable to VLBI parallax measurements. Most are fairly faint *Fermi* sources, and so disentangling any shock emission in the GeV region from pulsed emission will be challenging. However, they may be good candidates for TeV telescopes, especially redbacks with non-degenerate companions which can provide a dense field of seed photons for inverse Compton scattering.

This research was partially funded through the *Fermi* GI program, NASA grant #NNG10PB13P

TABLE 1. Black Widows and Redbacks in the Galactic Field

Pulsar*	P_s (ms)	$\dot{E}/10^{34}\dagger$ (erg/s)	d_{NE2001} (kpc)	P_B (hr)	M_c^{**} (solar)	ref.
Old Black Widows						
B1957+20 F	1.61	11	2.5	9.2	0.021	[14]
J0610−2100	3.86	0.23	3.5	6.9	0.025	[6]
J2051−0827	4.51	0.53	1.0	2.4	0.027	[20]
New Black Widows						
J2241−52 F	2.19	3.3	0.5	3.4	0.012	[17]
J2214+3000 F	3.12	1.9	3.6	10.0	0.014	[19]
J1745+10 F	2.65	1.3	1.3	17.5	0.014	[12]
J0023+09 F	3.05	??	0.7	3.3	0.016	[15]
J2256−1024 F	2.29	5.2	0.6	5.1	0.034	[5]
J1731−1847	2.3	??	2.5	7.5	0.04	[4]
J1810+17 F	1.66	??	2.0	3.6	0.044	[15]
New Redbacks						
J1023+0038 F	1.69	~ 5	0.6	4.8	0.2	[1]
J2215+51 F	2.61	??	3.0	4.2	0.22	[15]
J1723−28	1.86	??	0.75	14.8	0.24	[9]

* an F indicates a Fermi source

 \dagger assuming $1.4M_\odot$ and 10km radius** assuming $1.4M_\odot$ pulsar and $i = 90^\circ$

REFERENCES

1. A. M. Archibald et al., *Science* **324**, 1411 (2009).
2. A. M. Archibald et al., *this proceedings* (2011).
3. J. Arons, and M. Tavani, *ApJ* **403**, 249 (1993).
4. S. D. Bates et al., *this proceedings* (2011).
5. J. Boyles et al., *this proceedings* (2011).
6. M. Burgay, et al., *MNRAS* **368**, 283 (2006).
7. S. Chatterjee, et al., *ApJ* **698**, 250 (2009).
8. Cordes, J. M., & Lazio, T. J. W., arXiv:astro-ph/0207156 (2002).
9. F. Crawford III et al., *Bulletin of the American Astronomical Society* **42**, 604 (2010).
10. N. D’Amico, A. Possenti, R. N. Manchester, J. Sarkissian, A. G. Lyne, and F. Camilo *ApJL* **561**, L89 (2001).
11. P. B. Demorest, T. Pennucci, S. M. Ransom, M. S. E. Roberts, and J. W. T. Hessels, *Nature* **467**, 1081 (2010).
12. Freire, P. & Cognard, I. *private communication*
13. Fruchter, A. S., Stinebring, D. R., & Taylor, J. H., *Nature* **333**, 237 (1988).
14. A. S. Fruchter et al., *ApJ* **351**, 642 (1990).
15. J. W. T. Hessels, et al., *this proceedings* (2011).
16. H. H. Huang, and W. Becker, *A&A* **463**, L5 (2007).
17. M. J. Keith et al., *MNRAS in press* (2011).
18. S. R. Kulkarni and J. J. Hester, *Nature* **335**, 801 (1988).
19. S. M. Ransom et al., arXiv:1012.2862 (2010).
20. B. W. Stappers et al., *ApJL* **465**, L119 (1996).
21. B. W. Stappers, B. M. Gaensler, V. M. Kaspi, M. van der Klis, and W. H. G. Lewin *Science* **299**, 1372 (2003).
22. J. P. W. Verbiest, D. R. Lorimer, and M. A. McLaughlin *MNRAS* **405**, 564 (2010).